The luminosity of the Sun

Study time: 90 minutes

Summary

In this observational activity you will perform an experiment to measure the luminosity of the Sun by comparing its brightness with that of a light bulb.

> **Warning** Remember it is **very dangerous** to look directly at the Sun and on no account should you look at the Sun through any telescope or binoculars. Otherwise, you will suffer permanent eye damage, and perhaps blindness.

The experiment requires use of a *clear tungsten filament* light bulb of at least 100 W (it will not work with other types of bulb). These bulbs have been withdrawn from sale in the UK and you may therefore not be able to do the experiment yourself. However, an alternative online interactive version of this experiment will be available on the course website. If you perform the online version, you should still read all the notes (Introduction, Preparation and Making measurements sections) for the practical activity first so that you fully understand the experiment. The online version will provide instructions for taking measurements using the virtual experiment apparatus. The data analysis is the same for both experiments.

The luminosity of the Sun is its power output over all wavelengths and over all directions, as explained in Sections 1.2.1 and 1.4.2 of *An Introduction to the Sun and Stars*.

You should study the *Observational activities* booklet before undertaking this activity.

The study time indicates how long you will need for the observing session(s) and includes preparation and note taking; the observations themselves should take less time. Data analysis and writing up require additional time after the observing session.

Learning outcomes

The learning outcomes for the observational activities are grouped together at the front of the *Observational activities* booklet.

Introduction

A clear sky for only about one hour is required, and you will not need binoculars.

The luminosity of the Sun is measured by comparing it with a source of known luminosity, such as a tungsten bulb. The set-up is shown in Figure 1. When you view the sheet of paper from the Sun-facing side, the brightness of the oil-spot on the sheet depends on the flux density (illumination) provided by the tungsten bulb, and the brightness of the oil-free paper surrounding the spot depends on the flux density provided by the Sun. The distance, d_b, between the sheet and the bulb is varied until the oil-spot looks about as bright as the surrounding paper. The distance of the sheet from the bulb filament is then measured, and the solar luminosity calculated. An oil-spot used in this way constitutes what is known as Bunsen's oil-spot (or grease spot) photometer, named after the German scientist Robert Bunsen (1811–1899).

Further details follow – read through them all before you start.

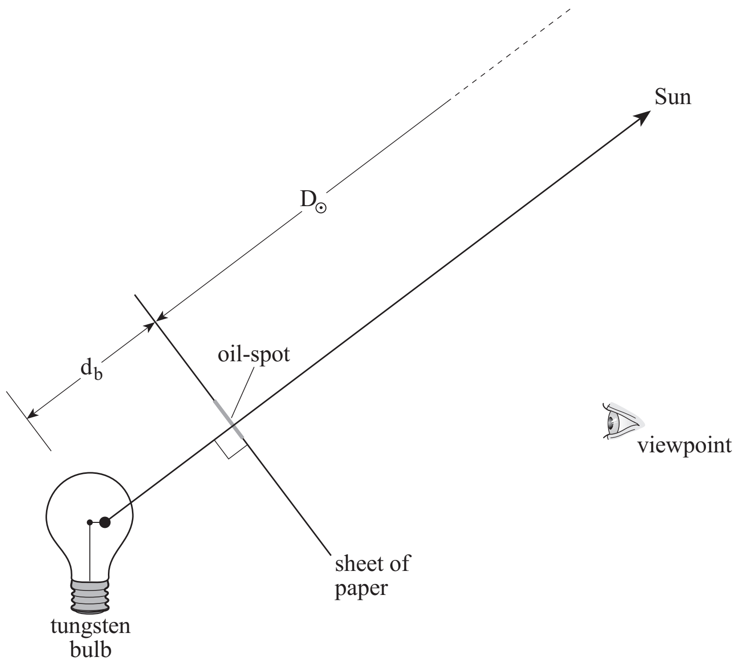

Figure 1 The observational set-up.

Preparation

You need a light source of known luminosity. A *clear* (not pearl) mains-operated *tungsten filament* bulb of 100 W (or better, a 150 W bulb if you can find one) is required for this experiment. The bulb has to be located out of doors, or near an open window through which the Sun shines. A table lamp with the shade removed makes an excellent receptacle for the bulb.

> Do take care with mains electricity, particularly if you are working out of doors. Also, note that the bulb will get hot.

The next task is to obtain the sheet of paper used to compare the two flux densities. The paper must be white, un-ruled, non-glossy, and of normal thickness – just the sort of paper commonly sold in pads in stationery shops or newsagents. A4 size is suitable.

When you are ready to make observations, put a spot of oil near the centre of the sheet. The spot must be no more than about 4 mm diameter. You can prepare the oil-spot by dipping a skewer in cooking oil, then removing nearly all the oil with a tissue, and then touching the skewer tip on the sheet for just an instant. The oil-spot tends to spread, and so it should be prepared within about an hour of when you want to use it.

Next, you need some means of holding the sheet steady, fairly near to the bulb, and roughly at right angles to the line from the filament to the Sun. This imaginary line should pass more or less through the oil-spot – see Figure 1. If the filament is fairly straight, then it should be roughly parallel to the sheet of paper. You could co-opt a second person to hold the sheet, otherwise some kind of support frame will have to be used.

You will also need a means of measuring the distance from the oil-spot to the filament when the oil-spot looks the same brightness as the surrounding paper. This distance will certainly not exceed 200 mm. Because the filament is somewhat inaccessible, we expect no great accuracy here.

The only other things you will need are

- these activity notes
- your activity notebook, plus something to write with
- a sky no more than partly cloudy, preferably within an hour of noon so that the Sun is about as high in the sky as it gets on any particular date.

Making measurements

Arrange the bulb, the sheet of paper and yourself as in Figure 1. In your activity notebook write down the date and time, whether the sky is clear (between any clouds) or hazy, the location of your observing site, details of your set-up, including the wattage of the bulb, and details of your technique, including how you will measure the distance between the oil-spot and the filament.

Vary the distance between the bulb and the sheet, keeping the sheet roughly perpendicular to the straight line from the filament to the oil-spot to the Sun, until the oil-spot looks about as bright as the surrounding paper. If the sheet is too close to the bulb then the oil-spot will look brighter than the surrounding paper. If it is too far from the bulb, it will appear darker. If your oil-spot is much larger than about 4 mm, the colour difference between the bulb and the Sun will make the brightness comparison difficult – this is why the oil-spot has to be small.

When the brightnesses are equal, measure the distance between the oil-spot and the filament as best you can.

Write down the distance in your activity notebook. Then move the paper away from the bulb, and repeat the procedure, to obtain another value of the distance. Carry on until you have recorded about ten values. And that's the end of your measurements!

Data analysis

The first task is to reduce your ten or so values of distance to a single value with its uncertainty, i.e. $d_b \pm \Delta d_b$. To do this, follow the procedure in Section 3.1 of the *Observational activities* booklet.

The next task is to understand the relationship between the Sun's luminosity and that of the bulb. We start with Equation 3.10 in Chapter 3 of *An Introduction to the Sun and Stars*. The flux density on the paper due to the Sun is given by

$$F_\odot = L_\odot/(4\pi D_\odot^2) \qquad (1)$$

where $L_\odot$ is the Sun's luminosity, and $D_\odot$ its distance from the paper. Likewise, the flux density on the other side of the paper due to the bulb is given by

$$F_b = l_b/(4\pi d_b^2) \qquad (2)$$

where l_b is the bulb's luminosity, and d_b its distance from the oil-spot. The action of the oil-spot is such that if the oil-spot has the same brightness as the surrounding paper, then, to sufficient accuracy, the flux densities are equal (probably within ±20%). In this case, from Equations 1 and 2,

$$L_\odot/(4\pi D_\odot^2) = l_b/(4\pi d_b^2)$$

and so

$$L_\odot = l_b(D_\odot/d_b)^2 \qquad (3)$$

To sufficient accuracy, $D_\odot$ is 1.50×10^{11} metres, l_b is the known wattage of the bulb, and you have measured the value of d_b. If there were no further considerations, then the Sun's luminosity could be calculated from Equation 3.

But there *are* further considerations!

Further considerations

(i) First, the solar flux density will have been somewhat reduced by absorption and scattering in the Earth's atmosphere. If you chose a clear day, and made your measurements within about an hour of noon, then for the UK in February/March, the solar flux density will have been roughly halved. You should thus *double* your value of $L_\odot$ to make a rough correction for this effect.

(ii) Second, Equations 1 and 2 assume that the sources radiate uniformly in all directions, and that we are at large distances compared with the sources' dimensions. This is close to the truth for the Sun, but for the lamp it is likely to be a poor assumption. State whether your value of $L_\odot$ has been made higher or lower by this assumption, but attempt no correction.

(iii) Finally, there is a big correction that you really *have* to make. It arises largely from the spectral response of the radiation detector that you have been using – your eyes. The spectral response of the eye is shown in Figure 2a (see p. 55), along with the solar spectrum, and in Figure 2b along with the shape of the spectrum of a black body at about the temperature of the tungsten bulb filament. The correction arises because the eye responds to a larger fraction of the Sun's radiation than it does to that of the bulb. You can see this from the shaded areas in Figures 2a and 2b, which represent these fractions (on the simplifying assumption that the eye responds uniformly between 0.5 μm and 0.6 μm, and not at all outside this range).

If the eye responds to a fraction $f_\odot$ of the Sun's luminosity, and to a fraction f_b of the electrical power put into the bulb, then Equations 1 and 2 become

$$f_\odot F_\odot = f_\odot L_\odot/(4\pi D_\odot^2)$$

and

$$f_b F_b = f_b l_b/(4\pi d_b^2)$$

and so, in place of Equation 3, we have

$$L_\odot = (f_b/f_\odot)\, l_b\, (D_\odot/d_b)^2$$

The value of the ratio ($f_b/f_\odot$) is approximately 0.45 for a 150 W tungsten bulb. The shaded areas in Figure 2 give a smaller ratio than this, but the shape of the spectrum of a tungsten bulb departs somewhat from the shape of a black-body spectrum, leading to a larger value of f_b than that implicit in Figure 2b. Indeed, the value of f_b would be even higher were it not for some of the electrical power put into the bulb being transferred to the air around the bulb and convecting away, rather than being radiated.

Putting these corrections (i) and (iii) together, we thus have

$$L_\odot = (2 \times 0.45)\, l_b\, (D_\odot/d_b)^2 \qquad (4)$$

You can now find your value of $L_\odot$.

The uncertainty in your value is, at the very least, that arising from the uncertainty Δd_b in d_b. To find the corresponding uncertainty in $L_\odot$, substitute $d_b - \Delta d_b$ and $d_b + \Delta d_b$ for d_b in Equation 4, and hence you will obtain respectively $L_\odot$(max) and $L_\odot$(min) (remember that the larger the value of d_b the smaller the value of $L_\odot$). The uncertainty $\Delta L_\odot$ is then given by

$$\Delta L_\odot = (L_\odot(\text{max}) - L_\odot(\text{min}))/2 \qquad (5)$$

This is a lower limit to the uncertainty in $L_\odot$, because correction (ii) was not made, and because corrections (i) and (iii), which were made, carry their own uncertainties. However, it is sufficient for you to quote the lower limit to the uncertainty based on Δd_b, and leave it at that. Do, however, remember to state whether correction (ii) would have made your value of $L_\odot$ higher or lower.

Conclusion

It is clear that your value of the Sun's luminosity will not be very accurate. Indeed, you could easily be out by a factor of two or more! But despite this inaccuracy, the activity does illustrate many of the problems that astronomers face in making measurements. Also, given the crudeness of the approach, it is quite something to get within even a factor of two!

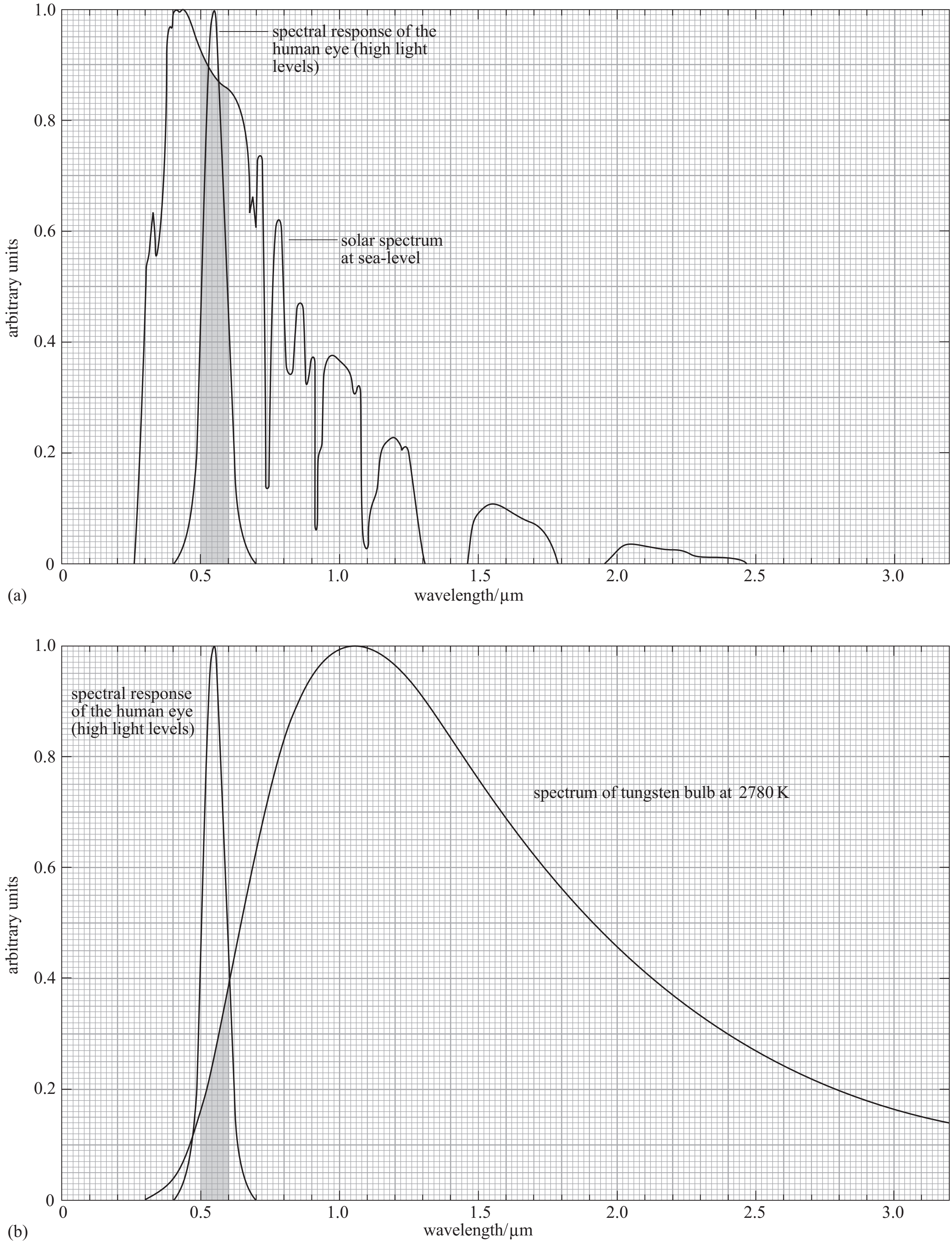

Figure 2 The spectral response of the human eye, and: (a) the solar spectrum; (b) the spectrum of a tungsten bulb (at 2780 K), assuming the spectrum of the tungsten bulb to have the shape of the spectrum of a black body.